Quantum Computing Trends

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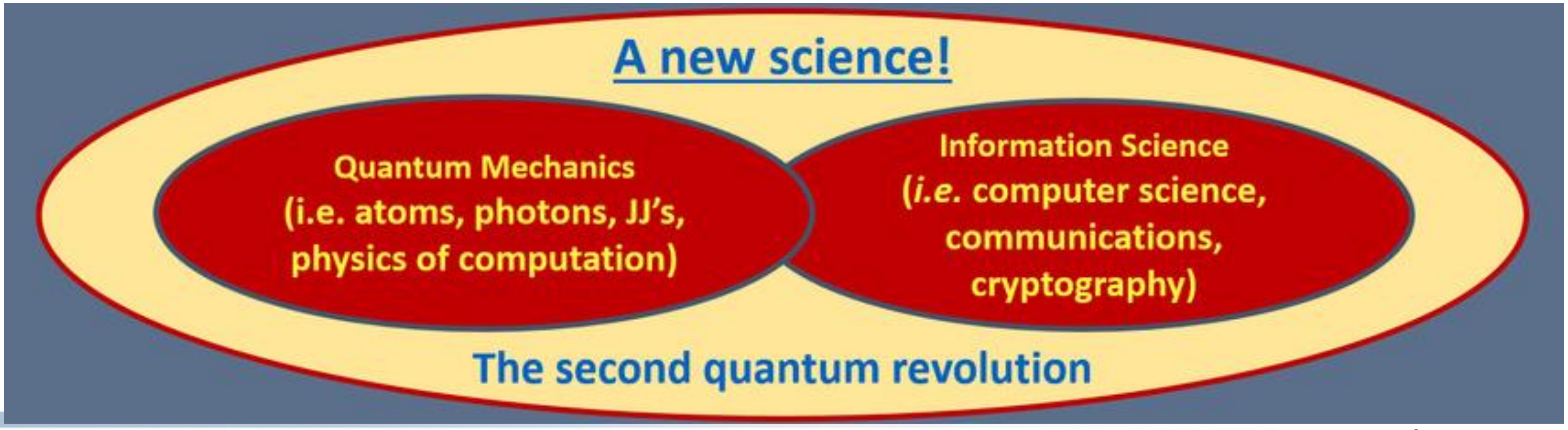
What is Quantum Information Science?

- **Quantum mechanics explains how world works at microscopic level, which governs behavior of all physical systems, regardless of their size. Arguably one of the greatest scientific discoveries on 20th century, leading to fundamental discoveries of how nature works**
- **Information science revolutionized how information is collected, stored, analyzed, manipulated, protected, and moved. It ushered new age of information in 20th century, with major repercussions in economic, social, and political spheres**
- **We see convergence of two 20th century greatest revolutions in the form of Quantum Information Science (QIS)**

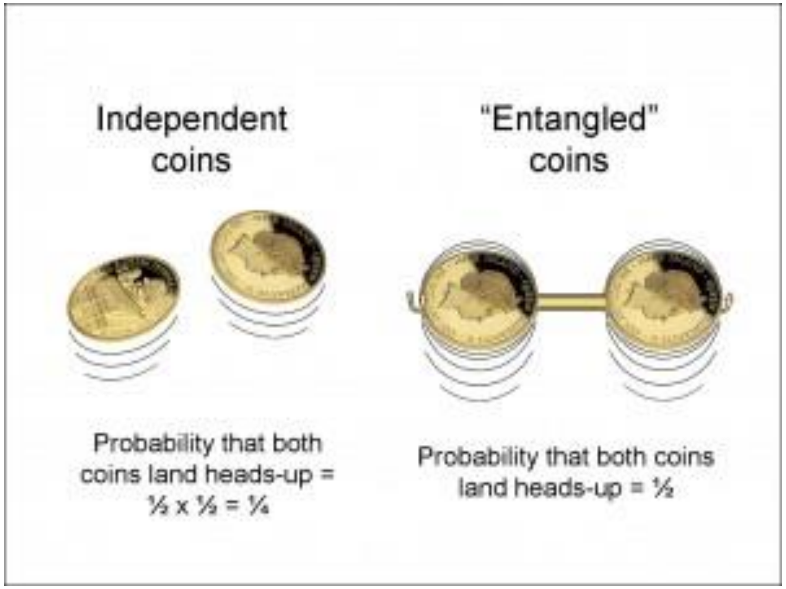


Credit: NIST

Quantum Information Science

- **QIS exploits unique quantum effects such as superposition, interference, and <u>entanglement</u> to obtain, compute, and transmit information in the ways that are superior compared to classical technology (digital, Newtonian)**
- **The key concept is entanglement ("spooky action at a distance", EPR pair). Works only for only very small object (electrons, photons, atoms etc). It is proven to be essential to achieve "quantum advantage" or for "quantum teleportation"**

Classical	
Outcome	Probability
00	1/4
01	1/4
10	1/4
11	1/4



Quantum	
Outcome	Probability
00	1/2
01	0
10	0
11	1/2

Key Concepts

- Qubit - basic unit of quantum information, which is the quantum version of the classical binary bit. It can exist in superposition – any state between 0 and 1
- Qubit fidelity – how long qubit stays coherent/operational
- Quantum effects - superposition, interference, and entanglement
- NISQ - Noisy Intermediate-Scale Quantum technology, often refers in the context of modern very noisy quantum computers
- QASM - Quantum Assembly used for programming quantum computers
- Quantum supremacy - demonstration of that a programmable quantum device can solve a problem (any problem) that no classical computer can solve in any feasible amount of time
- Quantum advantage - same as supremacy, but for useful applications

Quantum Supremacy Demonstration

Article

Quantum supremacy using a programmable superconducting processor

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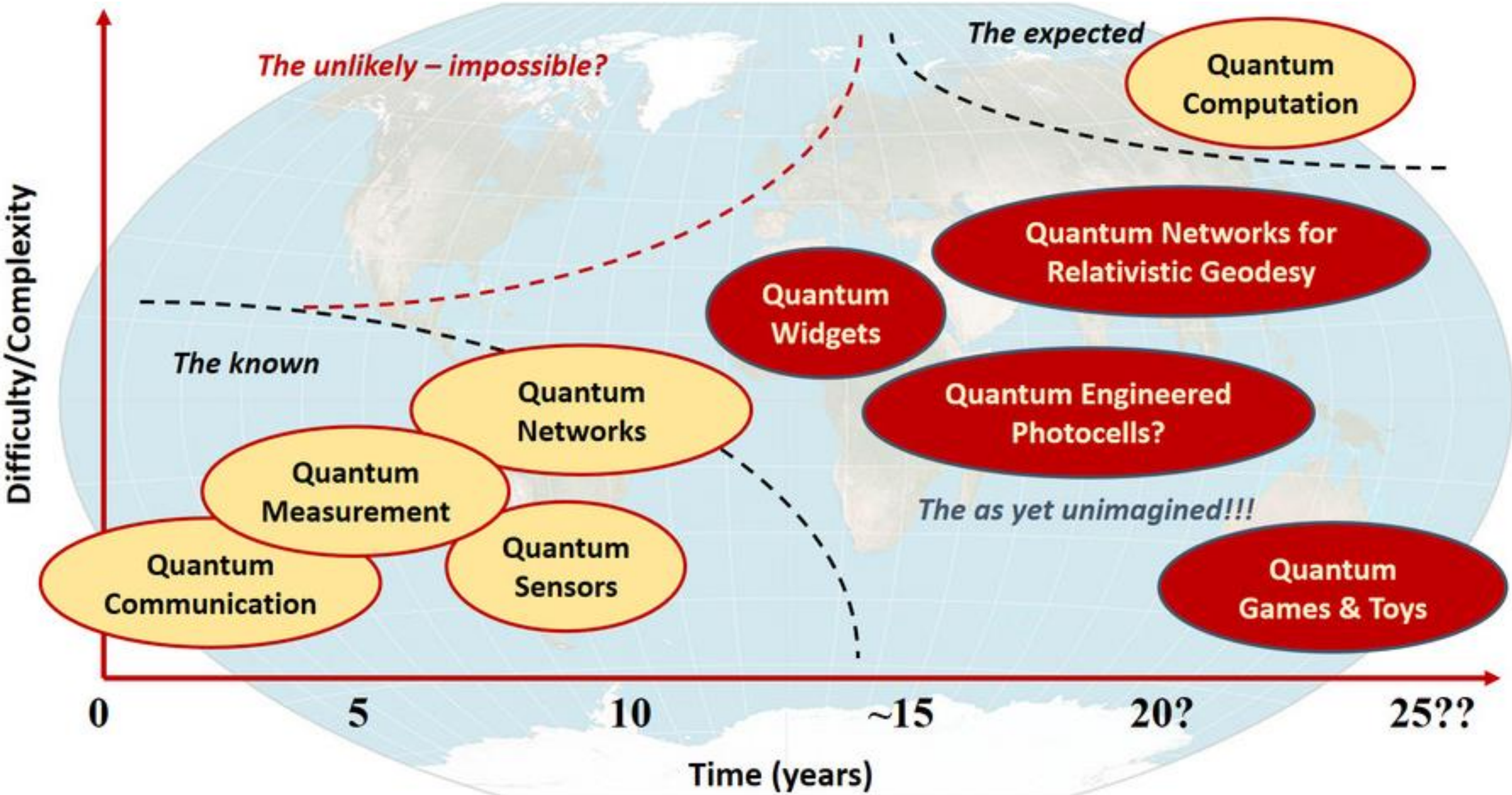
Google Sycamore processor (53 qubit device) takes about 200 seconds to sample one instance of a quantum circuit a million times. The equivalent task on Summit would take approximately 10,000 years. It is 1.6B times faster.

Quantum Applications



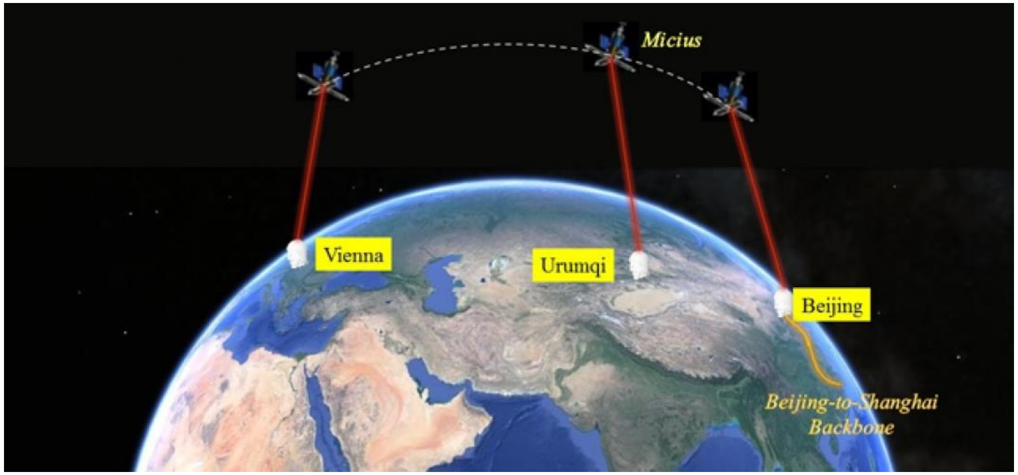
Credit: NIST

Quantum Applications

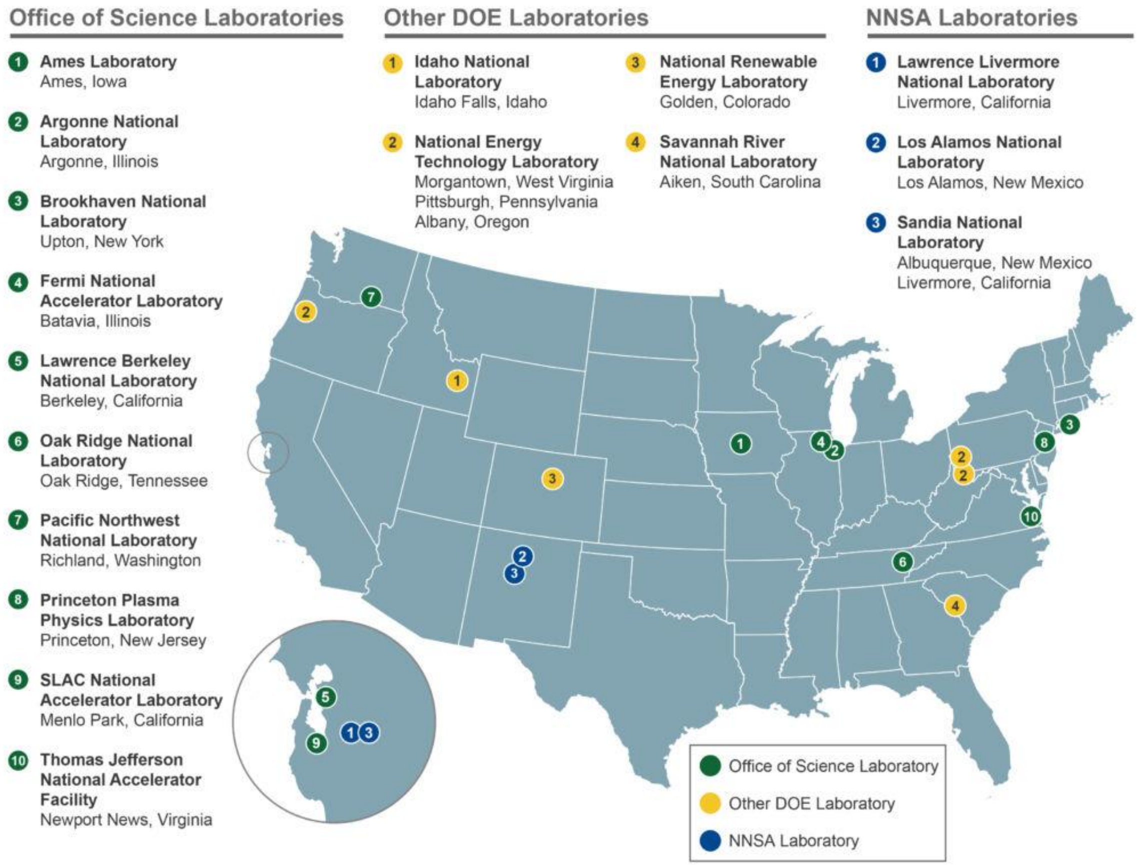
- Secure telecommunication (near future): quantum key distribution is an ultra-secure communication method that requires a key to decipher a message. If the message gets intercepted, no one else can read it.
- Quantum sensors (not far future): devices that exploits quantum entanglement to achieve a sensitivity or resolution that is better than can be achieved using only classical systems. Applications: astrophysics, high energy physics, military (quantum radars) etc.
- Scientific problems (far future): a number of NP-hard combinatorial problems can be solved efficiently on quantum computers (i.e. linear algebra and database search). Applications: quantum chemistry, traffic control, real-time risk analysis, financial, and forecasting etc.

Quantum Teleportation

- Chinese scientists set the record for the farthest quantum teleportation in 2017. It demonstrated that quantum teleportation works over distance of 870 miles. It paves the way to quantum internet
- Quantum-encrypted images by encoding them as strings of numbers based on the quantum states of photons and sent them across distances of up to 4,722 miles between Beijing and Vienna in 2018
- The best way to distribute quantum entanglement around the globe is via a massive constellation of orbiting satellites according to just published MIT report
- UChicago – Argonne – Fermilab 30 mile quantum network is under construction



U.S. Quantum Internet



DOE Unveiled blueprint for a U.S. Quantum Internet July 24, 2020.

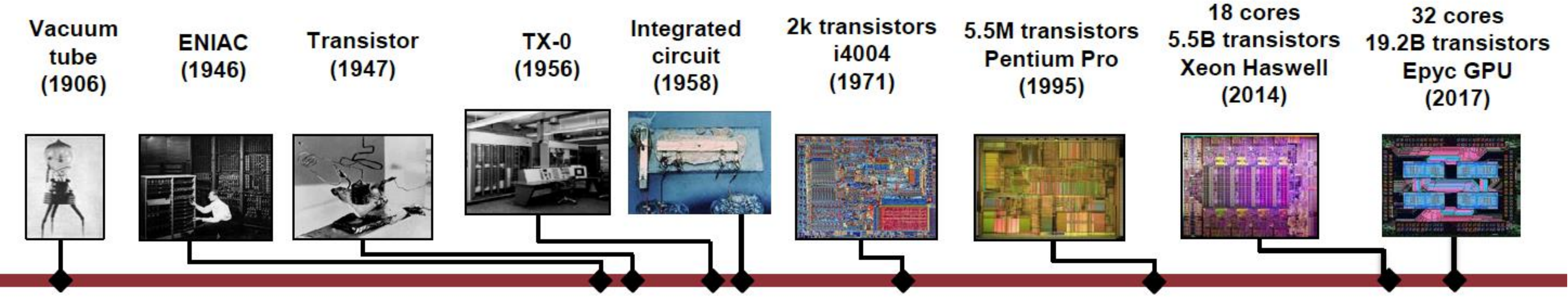
The initial plan is to connect up all 17 of their national labs to establish the backbone of the quantum internet. The ultimate goal is to build a multi-institutional ecosystem between laboratories, academia, and industry to transition from demonstration to operational infrastructure.

Publicly Announced National and International Initiatives in QIS

Nation	Initiative	Year Launched	Investment, Time frame	Scope
US	US Quantum Initiative	2020	Up to $625 over 5 years	National centers of QIS excellence (up to five centers for up to $25M/year)
China	National Laboratory for QIS	2018	$11.4B	Centralized quantum research facility
EU	Quantum Technologies Flagship	2018	$1.1B over 10 years	Quantum communication, metrology and sensing, simulation, computing, and fundamental science
Russia	Russian Quantum Initiative	2019	$780M	Quantum computers, quantum computing, quantum communication, quantum sensors
Germany	German Quantum Imitative	2019	$712M	Quantum computers, quantum computing, quantum communication, quantum sensors
UK	UK National Quantum Technologies Program	2014	$358M over 5 years	Sensors and metrology, quantum enhanced imaging, quantum communications technologies

Hardware timeline

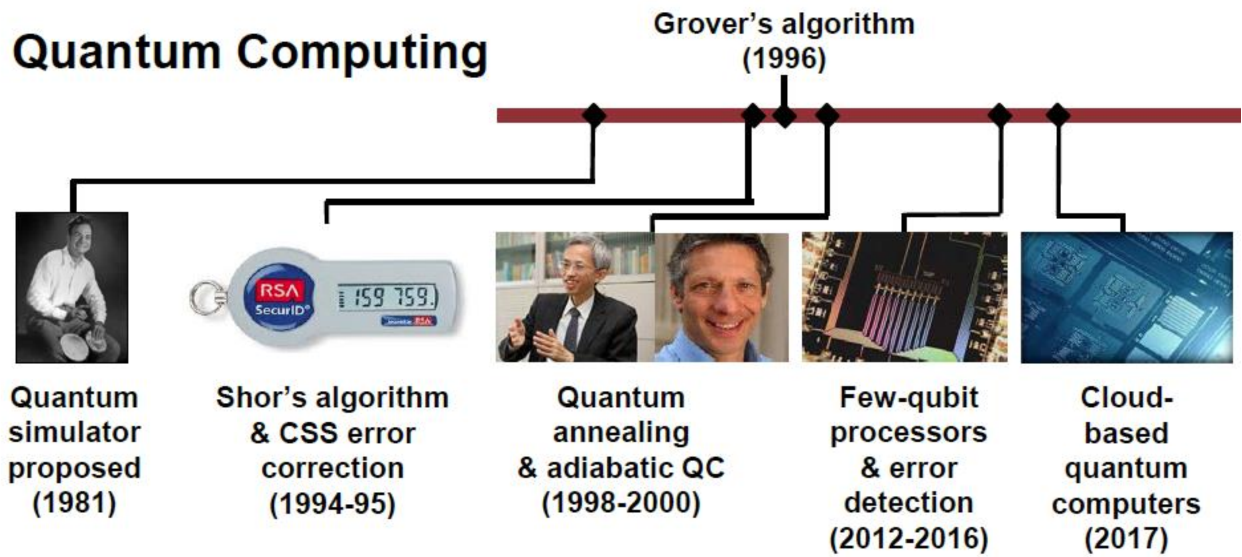
Classical Computing (Electronic)



Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to prototype to useful machines takes time.

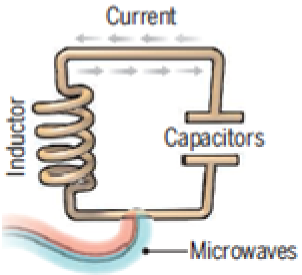
Quantum Computing

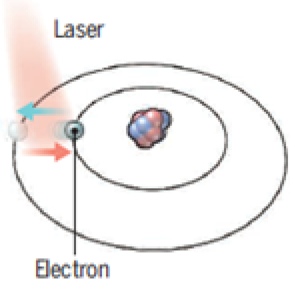


Credit: MIT

Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space



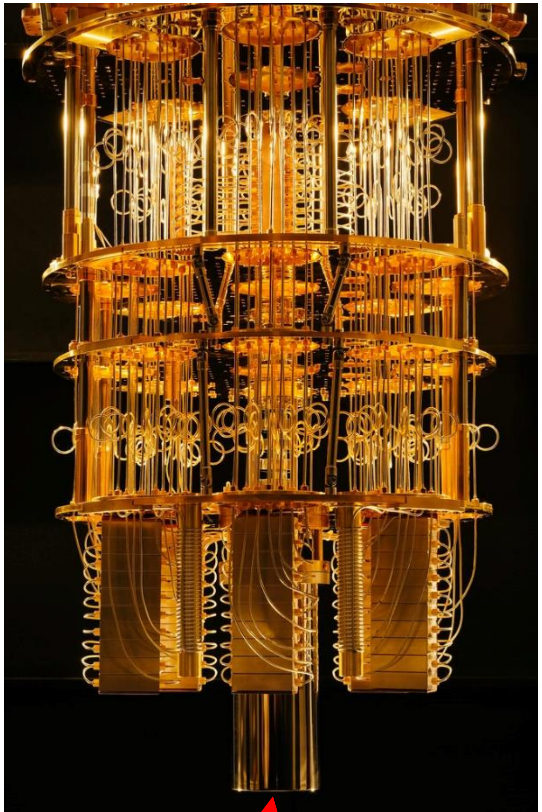


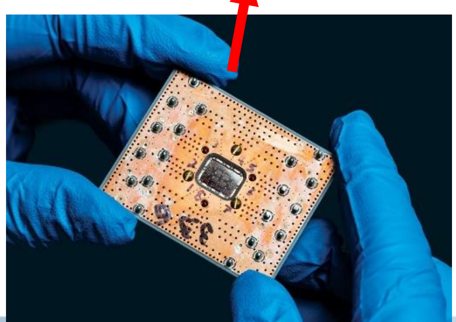
Computers are ranked by number of qubits decoherency time

		Superconducting (IBM, Google, Rigetti)	Trapped ions (IonQ, U. of Innsbruck)
Qubit Modality	Materials	Al on the Si substrate	Yb+, Ca+, Sr+, Be+, Ba+, Mg+
	Type	Transmon	Optical transitions
	Control	Microwaves	Microwaves+optics
	State	Junction phase	Atomic state of electron
Approximate Decoherency Times (ns)		~100-200	Very long
	1qb gate	10	5,000
	2qb gate	40	50,000
Fidelity	1qb gate	99.9%	99.999%
	2qb gate	99.0%	99.5%
Speed (MHz)	1qb gate	100.00	0.20
	2qb gate	25.00	0.02

Modern CPUs:
~3 GHz, 100% fidelity

IBM quantum computers





The key piece of the Quantum Computer is the Dilution Refrigerator
Working Temperature 15 mK uses mix of
$^{3}He/^{4}He$

Source: IBM Research

Available and announced quantum computers

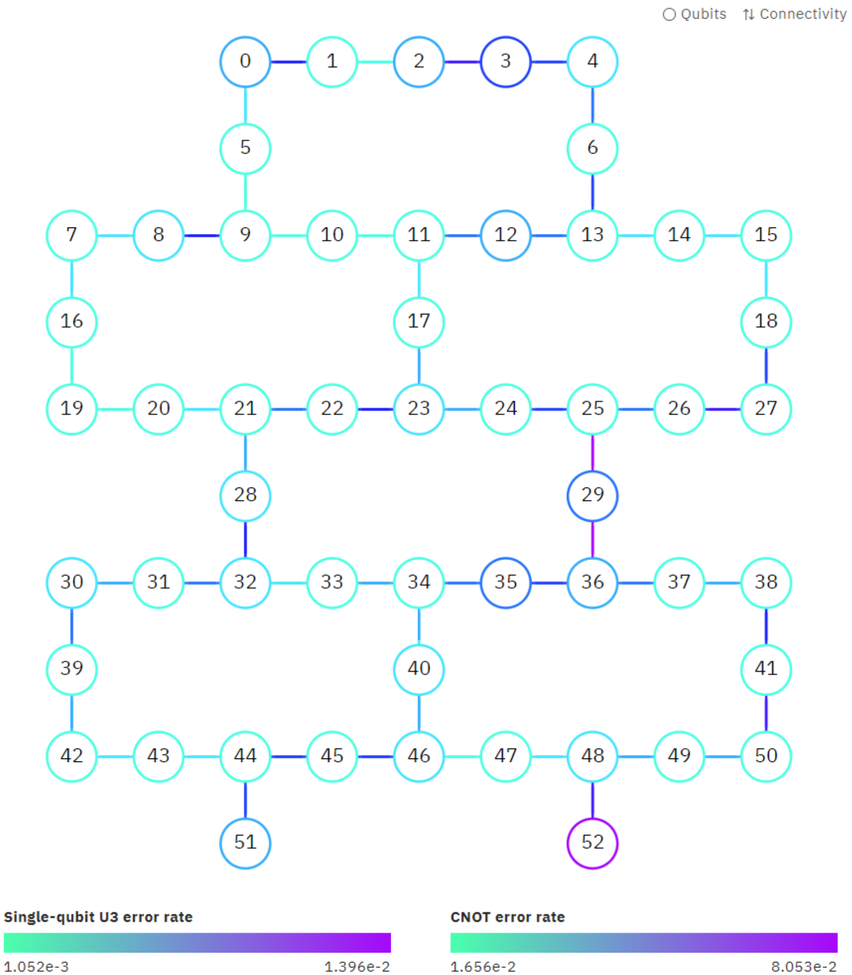
Company	Operational	Cloud Access	Framework	Announced
IBM	53 qubits	Open to Q hub members	QisKit	100+ qubit in 2021?
Rigetti	19 (8) qubits	Access by request	Forest	50+ qubits in 2020?
Google	53 qubits	No access	Cirq	72 qubit chip announced March 2018
Intel	?	No access	?	49 qubit chip announced Jan. 2018
Alibaba	11 qubits	?	Aliyun	
IonQ	11 qubits	No access	AWS and Azure	
D-Wave	2000Q (~60 qubits)	Open (1 minute per month)	Leap	5000Q announced in 2019

IBM quantum computers

Everybody can get access through cloud (IBM Quantum Experience):
https://quantumexperience.ng.bluemix.net/qx/signup

Available devices (public and Q hub):

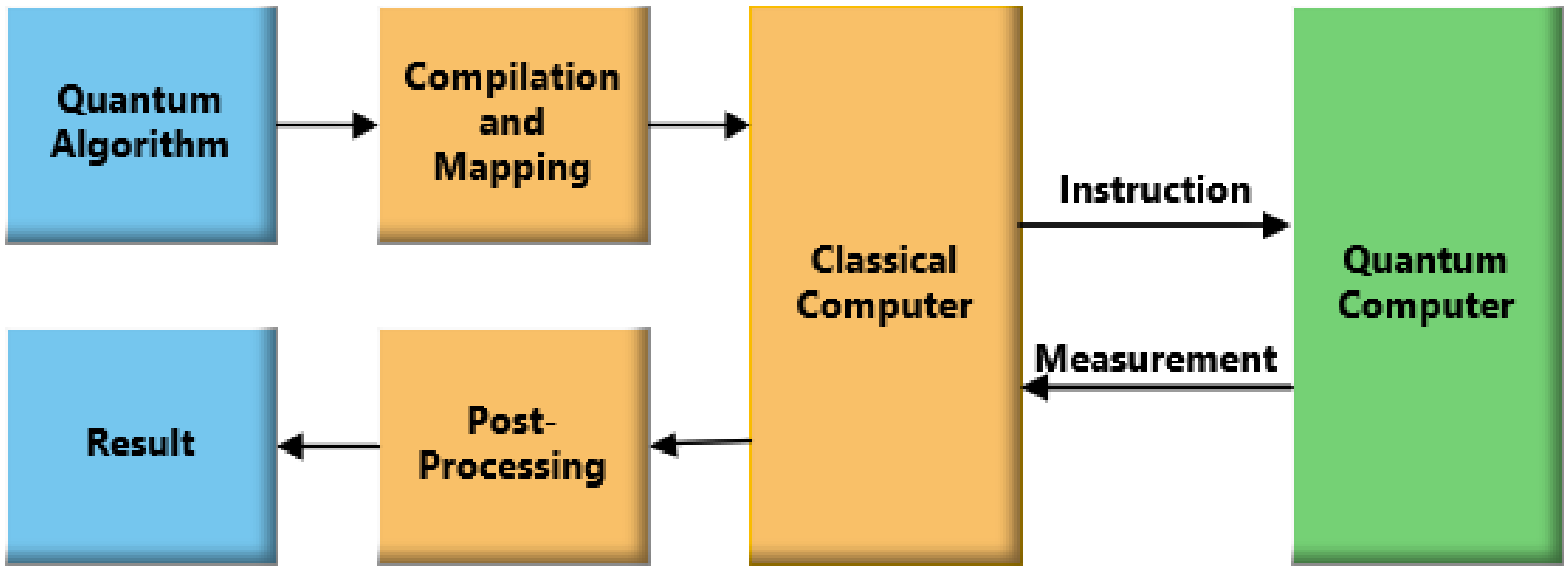
Qubits in device	Number of devices	Public
5	6	6
15	1	1
20	4	0
53	1	0



Reality check

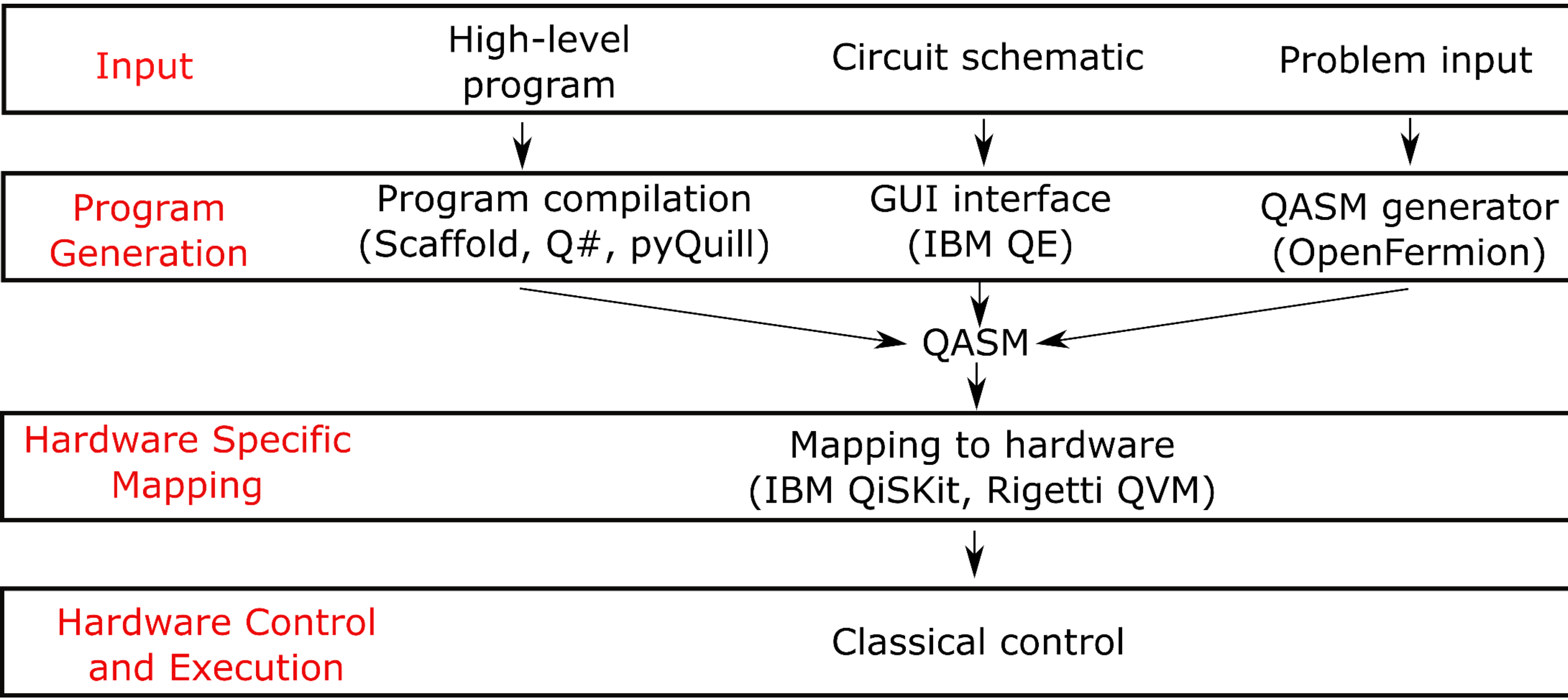
- We have 53 noisy qubits (need millions for computation)
- Short decoherency time limits execution up to 10-100 gates maximum (need millions)
- Slow gates MHz (need GHz)
- Poor connectivity (for superconducting quantum computers)
- Slow I/O
- Quantum Winter II for Quantum Computing in future?

Hybrid Quantum/Classical Computing System

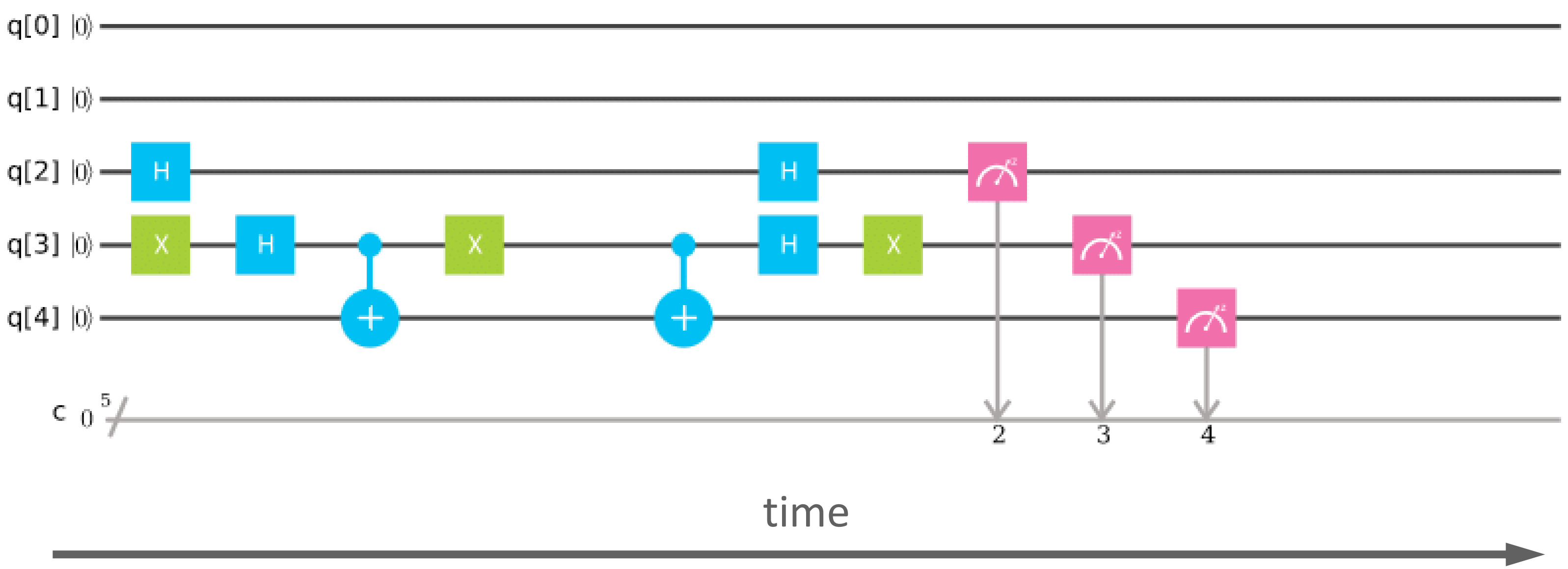


A high-level block diagram of a quantum computing system, where colors represent different levels of abstractions. Typically three levels are involved: a user level (blue), classical computation and control (yellow), and QC system (green). A quantum algorithm is compiled and mapped into a native set of instruction for the target quantum computer. The measurement of quantum register after postprocessing becomes the result.

Quantum software stack



Quantum circuits

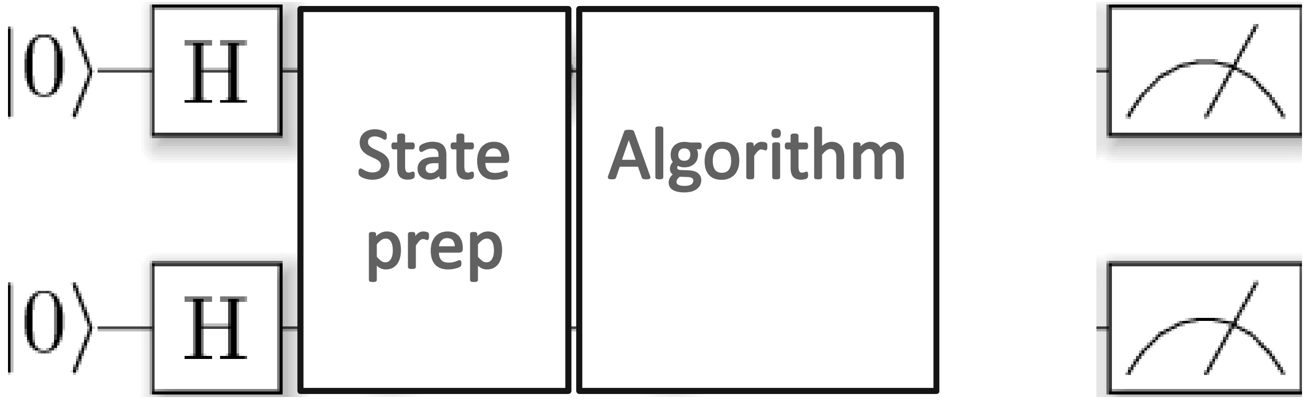


Quantum computers are programmed by using Quantum Assembly (QASM)
QASM standards: MIT QASM, IBM OpenQASM 2.0, LANL QASM, Atos QASM etc.

Qbit q2 Qbit q3 Qbit q4 H q2 X q3 H q3 CNOT q3, q4	X q3 CNOT q3, q4 H q2 H q3 X q3 measure q0 measure q1

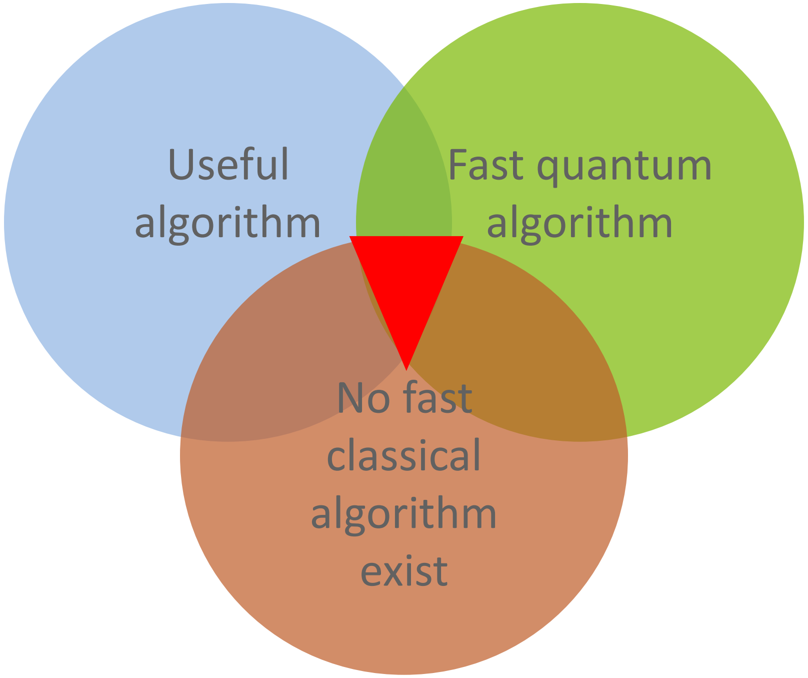
A typical structure of a quantum algorithm

Initialize → Maximum superposition → State preparation → Logic Gates → Minimum superposition → Measurement



- First part of the algorithm is to make an equal superposition of all 2^n states by applying H gates
- The second part is to encode the problem into this states; put phases on all 2^n states
- In the third part interfere all these states back to a few outcomes containing the solution

Quantum Algorithms



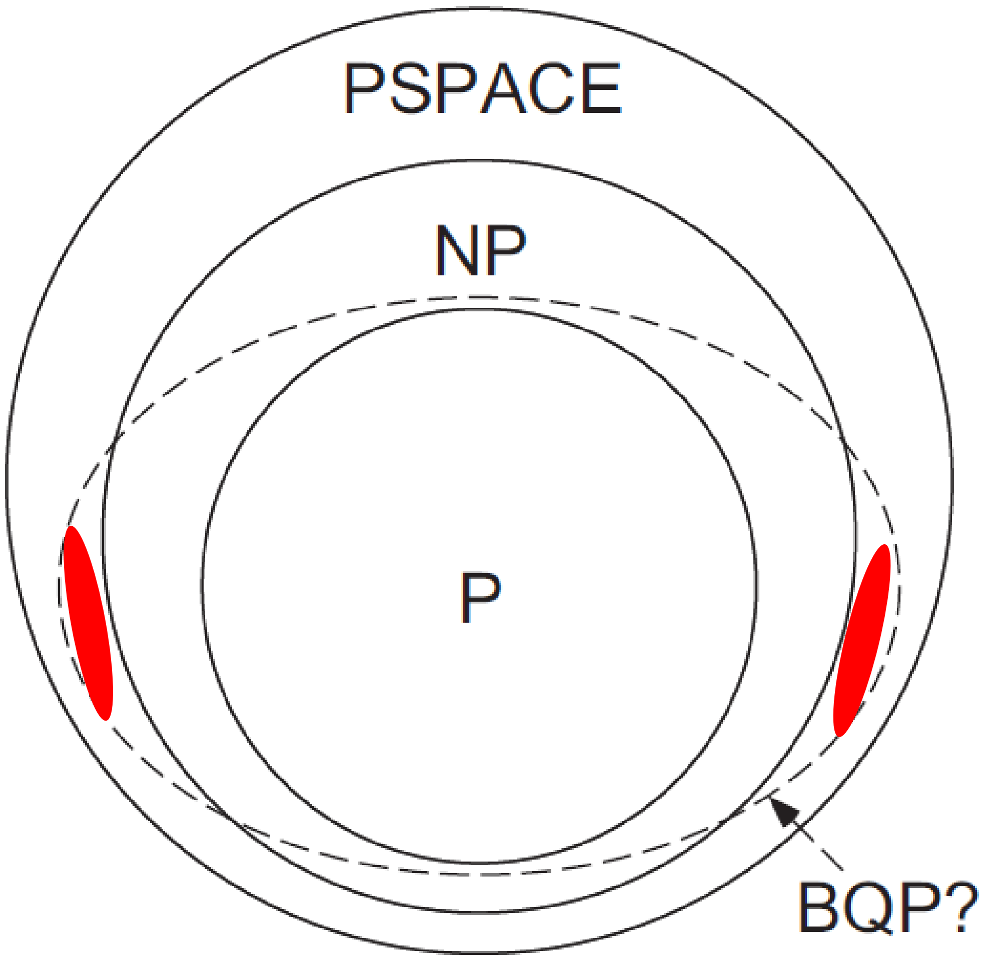
- There are two known classes algorithms hitting all three circles:
- Four main fundamental algorithms expected to provide a speedup over their classical counterparts: Shor's factoring algorithm, Grover's search algorithm, HHL’s linear system solver, and quantum simulation
- Quantum machine learning?

Quantum Algorithms

Algorithm	Classical resources	Quantum resources	Quantum speedup	Requirements
Quantum simulation	2^N	$\sim N^6$	Exponential	100+ qubits, millions of gates
Factorization	2^N	N^3	Exponential	200+ qubits, millions of gates
Solving linear systems	N^2	Log(N)	Exponential	Millions of gates and qubits
Unstructured search	N	$\sqrt{N}$	$\sqrt{N}$	Millions of gates and qubits

N-complexity of the problem

The Power of Quantum Computation



P = solved in polynomial time
NP = verified in polynomial time
PSPACE = solved in polynomial space

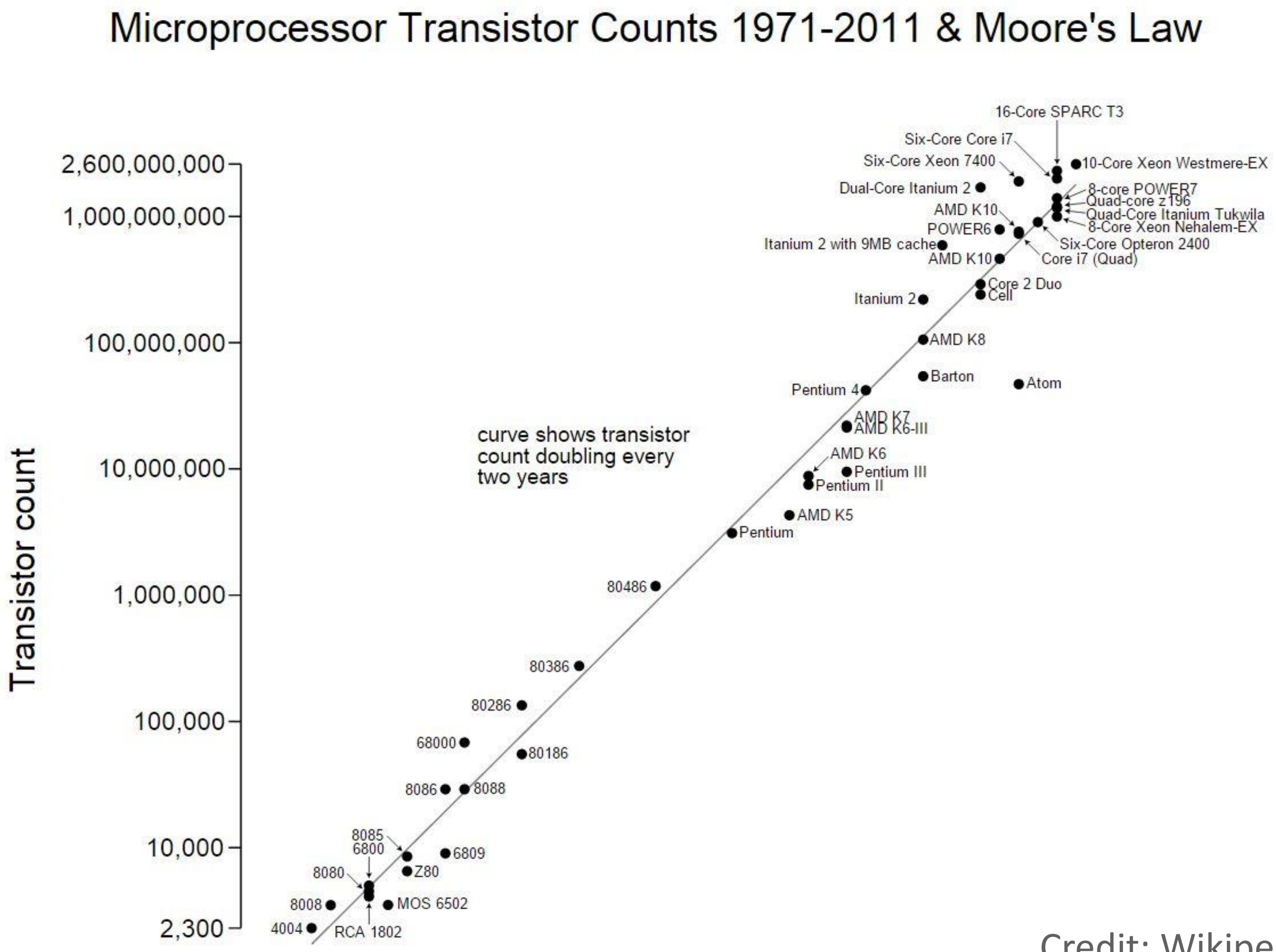
We do not know whether

P != NP

PSPACE is bigger than NP

BQP (Bounded error Quantum Polynomial time) is the class of decision problems solvable by a quantum computer in polynomial time, with an error probability of at most 1/3 for all instances

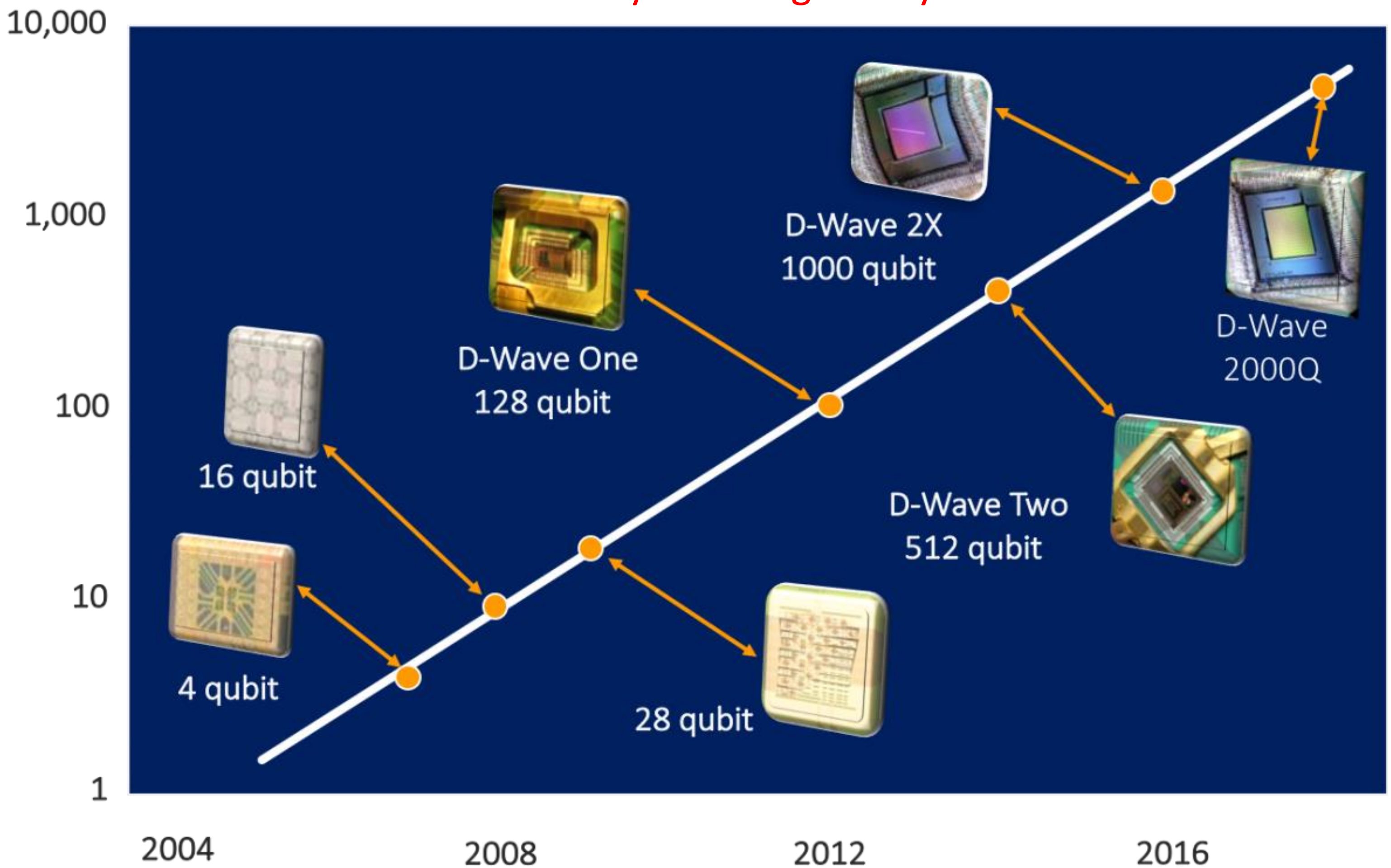
Moore's Law



Credit: Wikipedia

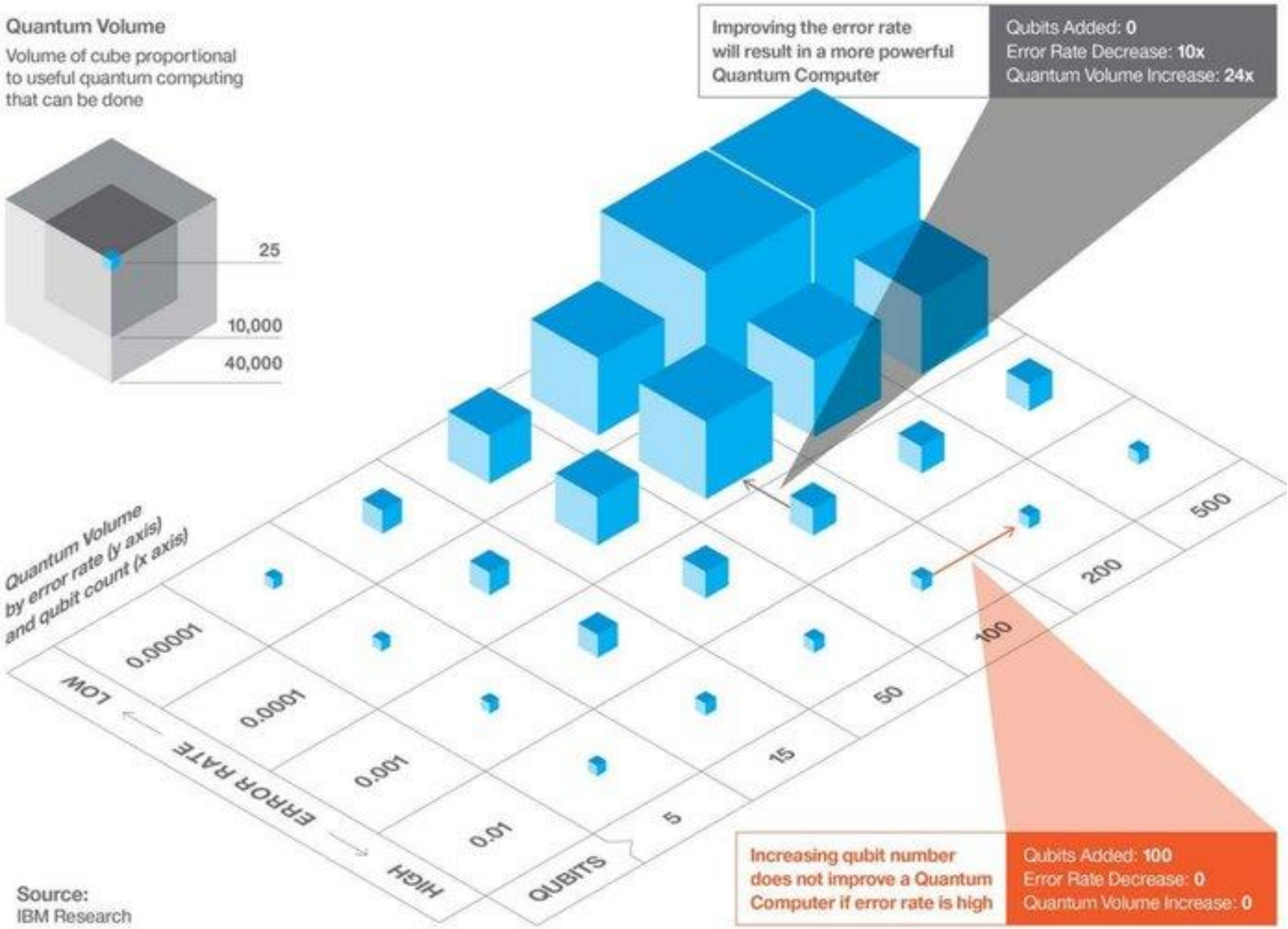
Rose's Law

For the past 10 years, the number of qubits on D-Wave's QPUs has been steadily doubling each year

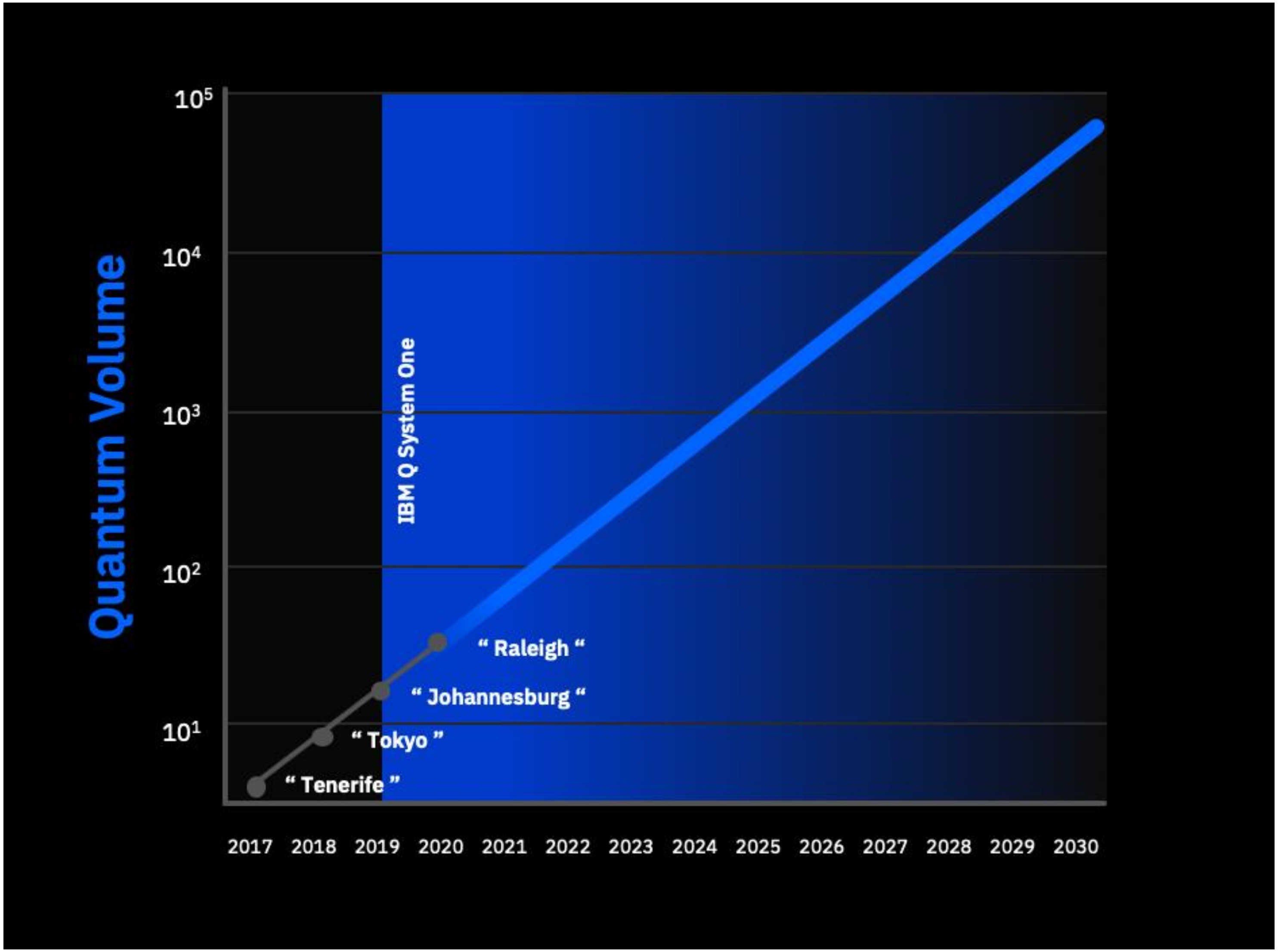


Credit: D-Wave

Quantum Volume



IBM Quantum Volume Roadmap



Credit: IBM

Acknowledgments

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Quantum Simulators

Simulator	Advantages	Disadvantages
Intel-QS	highly scalable C++ HPC code (MPI/OpenMP), freely available from Git	under development, no documentation, lacking sophisticated error models
ProjectQ	easy to use Python code, freely available from Git, works with OpenFermion	no MPI implementation, lacking documentation, lacking error models
QuaC	time dynamics, scalable code, freely available from Git, error models	under development, poor documentations, depends on PETSc
Atos	robust commercial package, easy to use, excellent documentation, error models	not freely available, no MPI implementation

Simulating Quantum Computers On Classical Computers

- Simulating a quantum gate acting on N qubits needs $O(2^N)$ memory and operations

Qubits	Memory	Time per operation
10	16 KB	Microseconds on a smartwatch
20	16 MB	Milliseconds on a smartphone
30	16 GB	Seconds on a laptop
40	16 TB	Seconds on a PC cluster
50	16 PB	Minutes on modern supercomputers
60	16 EB	Hours on post-exascale supercomputers?
70	16 ZB	Days on supercomputers in distant future?